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# Muon Collider Physics at Very High Energies<sup>1</sup>

M. S. Berger

*Physics Department, Indiana University, Bloomington, IN 47405*

**Abstract.** Muon colliders might greatly extend the energy frontier of collider physics. One can contemplate circular colliders with center-of-mass energies in excess of 10 TeV. Some physics issues that might be relevant at such a machine are discussed.

## INTRODUCTION

The large mass of the muon compared to that of the electron results in a large suppression of bremsstrahlung radiation. Consequently it is possible to consider building circular colliders with energies in the multi-TeV regime [1]. Muon colliders have been proposed as Higgs factories and more recently as neutrino factories, but the long-term goal of muon colliders should be to extend the energy frontier. It is not clear at the present time whether advances in accelerator technology will result in electron-positron machines achieving energies of several TeV. In this workshop first attempts were made to explore the feasibility of muon colliders with energies of at least 10 TeV.

It is hard to know what kind of physics might present itself in the 10-100 TeV mass range. After all, physicists have been arguing for a long time about the physics that will manifest itself at the Large Hadron Collider (LHC). The LHC, linear electron-positron colliders, and perhaps muon colliders should give us some clue as to what to expect at the following generation of machines. It is easy to imagine scenarios where a new collider might be necessary, but it is impossible to motivate a specific energy at this time. We can only speculate as to what physics might appear at the LHC or future linear colliders.

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## LUMINOSITY REQUIREMENTS

The figure of merit for physics searches at a muon collider is the QED cross section  $\mu^+\mu^- \rightarrow e^+e^-$ , which has the value

$$\sigma_{QED} = \frac{100 \text{ fb}}{s \text{ (TeV}^2\text{)}} \quad (1)$$

To arrive at a simple estimate of the integrated luminosity needed to study new physics, we assume

$$\left( \int \mathcal{L} dt \right) \sigma_{QED} \gtrsim 1000 \text{ events} \quad (2)$$

Then the luminosity requirement for this number of events to be accumulated in one year's running is

$$\mathcal{L} \gtrsim 10^{33} \cdot s \text{ (cm)}^{-2} \text{ (sec)}^{-1}$$

For the colliders with the center-of-mass energies considered at this meeting:

- $\sqrt{s} \simeq 10 \text{ TeV}$ , requiring

$$\int \mathcal{L} dt \gtrsim 1 \text{ (fb)}^{-1}, \quad \mathcal{L} \gtrsim 10^{35} \text{ (cm)}^{-2} \text{ (sec)}^{-1}$$

- $\sqrt{s} \simeq 100 \text{ TeV}$ , requiring

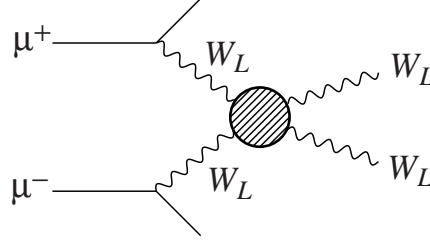
$$\int \mathcal{L} dt \gtrsim 100 \text{ (fb)}^{-1}, \quad \mathcal{L} \gtrsim 10^{37} \text{ (cm)}^{-2} \text{ (sec)}^{-1}$$

These luminosities are extremely high, of course, and it is not clear if experiments can be performed in such an environment.

## ELECTROWEAK SYMMETRY BREAKING

A 10 TeV muon collider might be very useful for exploring the physics responsible for electroweak symmetry breaking. If Higgs bosons with  $m_H < \mathcal{O}(800) \text{ GeV}$  do not exist then interactions of longitudinally polarized weak bosons ( $W_L, Z_L$ ) become strong and can be probed by studying vector boson scattering as shown in the figure. Therefore, new physics must be present at the TeV energy scale. While one can study strong  $W_L W_L$  scattering at the LHC, linear colliders, or  $\mu^+\mu^-$  colliders with a few TeV center-of-mass energy, it might become necessary to go to higher

energies to fully explore the multitude of resonances. Indeed we are still studying the analogous spectrum of QCD today.



## FERMION MASS GENERATION

The mechanism responsible for fermion masses and the mechanism breaking the electroweak symmetry are the same in the Standard Model. A Higgs scalar acquires a vacuum expectation value giving rise to massive gauge bosons and (through Yukawa couplings) masses for the fermions. However, it need not be the case that these mechanisms are the same, and technicolor models were the most prominent examples of theories where the fermion masses arise from a different sector from that responsible for the electroweak symmetry breaking. Hence one should keep an open mind about the origin of fermion masses. Very general constraints one can place on the physics of fermion mass generation are unitarity bounds. The relevant bound for fermions scattering into longitudinally polarized vector boson  $V_L$ ,

$$f\bar{f} \rightarrow V_L V_L, \quad (3)$$

is the Appelquist-Chanowitz bound [2] which states that unitarity is violated at the scale

$$\Lambda_f < \frac{8\pi v^2}{\sqrt{3N_c}m_f}, \quad (4)$$

where  $v = (\sqrt{2}G_F)^{-1/2}$  is the electroweak vev and  $N_c$  is the number of colors of the fermion. In the Standard Model this unitarity violation is cured by the inclusion of the  $s$ -channel Higgs exchange diagram. The strongest bound comes for the heaviest fermion the top quark for which  $\Lambda_t \approx 3$  TeV, indicating that some new physics must occur below this scale.

For a muon one gets  $\Lambda_\mu \approx 8,000$  TeV. So if the physics responsible for the muon mass saturates this bound, it is beyond the reach even of a 10-100 TeV muon collider. But one does not really expect that the bound is saturated, but rather that the fermion masses are all generated at a common scale with some masses suppressed by some approximate flavor symmetries. In light of the lower value of  $\Lambda_t$ , one might expect a 10 TeV collider to provide important insight into fermion

mass generation if Nature is not so kind to provide a elementary scalar particle. In the typical case one expects the resonances to be broad. In some scenarios [3], one can have strongly interacting Higgs sectors with narrow resonances for which a small energy spread might be helpful.

One can also study the unitarity violation in the subprocess  $V_L V_L \rightarrow t\bar{t}$ , analogous to the case discussed in the previous section for electroweak symmetry breaking. This process could also be sensitive to new physics responsible for the fermion masses, and one would measure the cross sections for  $\mu^+ \mu^- \rightarrow \nu \bar{\nu} t\bar{t}$  and  $\mu^+ \mu^- \rightarrow \mu^+ \mu^- t\bar{t}$ , and in scenarios where the unitarity is saturated, one might need the energy reach of a very high energy muon collider to probe these strong interactions.

## GAUGE BOSONS

A favorite target for new physics is the possibility of new gauge bosons beyond those found in the Standard Model. One might first reveal the existence of these particles via radiative return [4] whereby a vector boson with mass less than the center-of-mass energy is produced in association with an energetic photon. Alternatively one could pinpoint the mass of the vector boson by doing precision measurements of the couplings and asymmetries at energies below the vector boson mass. In either case, one would ultimately want to build a collider with an energy equal to the mass of the vector boson and take advantage of the resonance cross section. An important consideration then is the beam energy spread of the muon collider. The width of the vector boson should scale linearly with its mass. The expectations for a 10 TeV collider is that the energy spread  $\sigma_E/E$  should be something like  $10^{-4} - 10^{-3}$  [5], so the spread should be much smaller than the resonance peak in the typical case.

## SUPERSYMMETRY

It is possible that the LHC and linear colliders will uncover only part of the supersymmetric (SUSY) spectrum. In fact the lightest two generations of squarks and sleptons might appear at the multi-TeV scale. The absence of certain supersymmetric partners being produced below the TeV energy scale would certainly compel us to go to higher energies.

Beyond the discovery of all the superpartners to the Standard Model particles, another possible role for a very high energy muon collider would be to uncover an entirely new sector responsible for the dynamical breaking of supersymmetry. In gravitationally mediated SUSY breaking, the dynamical sector is hidden and couples only via gravitational couplings to the supersymmetric Standard Model particles. However other scenarios of SUSY breaking are possible, and these can be directly probed with sufficiently energetic collisions. In gauge mediated SUSY breaking scenarios, for example, there is just such another sector (known as the messenger sector) occurs at a scale beyond that which can be probed at the LHC.

This messenger sector might perhaps be accessible at a very high energy muon collider. The LHC might indirectly provide clues about the source of SUSY breaking by measuring the spectrum of superpartners and perhaps seeing radiative decays in the case of gauge mediated SUSY breaking. In fact by measuring the location of displaced vertices (relative to the interaction point) from the radiative decay of the next-lightest supersymmetric particle one can put a constraint on the scale of the gauge mediation sector as first suggested in a Very Large Hadron Collider study [6].

## COMPTON BACKSCATTERING

It seems at first peculiar to consider backscattering photons off of a muon beam. After all, the reason to employ muon beams rather than the electron beams is to decrease electromagnetic radiation. Eventually however, even for muons, bremsstrahlung radiation would again become a problem at sufficiently high energies in a circular collider. At the energies contemplated here, one can reconsidering employing Compton backscattering to produce photon beams of comparable energies. Kinematics dictates that the highest energy of a backscattered photon that can be obtained is given by

$$\omega_{\max} = \frac{x}{1+x} E_{\text{beam}} , \quad (5)$$

where

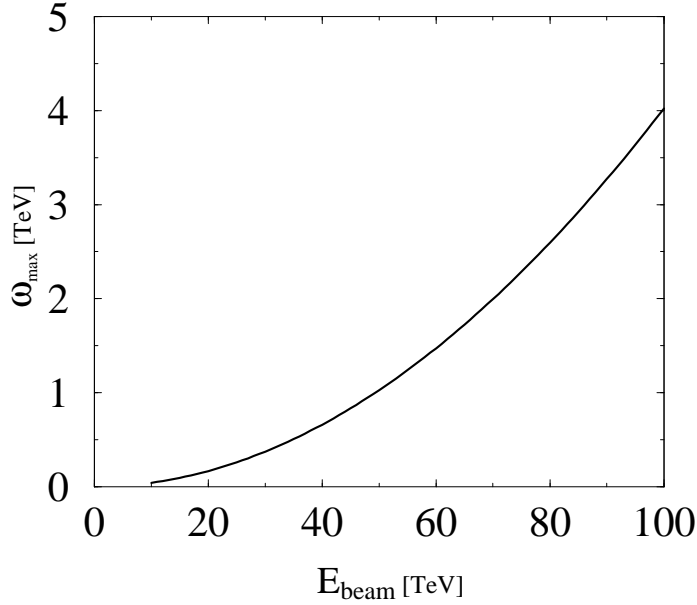
$$x = \frac{4E_{\text{beam}}\omega_{\text{laser}}}{m_{\mu}^2} . \quad (6)$$

Assuming an incident laser with energy  $1.17 \text{ eV}^2$ , one obtains maximum backscattered photon energies (shown in the figure) which are still much smaller than the incident muon beam energy. A more energetic photon source would be needed to fully realize the backscattered photon option even at the extremely high muon

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<sup>2)</sup> For definiteness we take a neodymium glass laser with  $\omega_{\text{laser}} = 1.17 \text{ eV}$  which is often considered for Compton scattering at a linear  $e^+e^-$  collider. In any case, one expects the laser energy to be in the few eV range.

energies considered here.



## CONCLUSIONS

It is difficult to motivate a very high energy muon collider without information that will be gleaned after years of operation of the LHC and linear colliders. However, if the past history of particle physics has taught us anything it is that the most important progress has occurred by going to higher and higher energies. It will be interesting in the coming years to learn whether multi-TeV muon colliders are realistic and economical.

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